WATERTOWN ARSENAL LABORATORIES

GEOMETRY OF HIDDEN DEFECTS DETERMINED BY ULTRASONIC PULSE ANALYSIS AND SPECTROSCOPY

TECHNICAL REPORT WAL TR 830.5/5

BY

OTTO R. GERICKE

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AD

Ultrasonic spectroscopy

Flaw determination

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ABSTRACT

A novel ultrasonic test method is described utilizing ultrasonic signals which contain a broad band of frequencies, and, in analogy to optics, can therefore be considered as "white" ultrasonic pulses. The form and spectral energy distribution, or "color", of such ultrasonic pulses is influenced by the geometry of a defect from which they are reflected. Hence, an analysis of the defect echo yields information on the defect configuration.

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CONTENTS

INTRODUCTION

Defects concealed in metals or other solid materials can be detected by ultrasonic inspection. The test procedure predominantly employed for this purpose is generally referred to as the ultrasonic pulse echo method and is in principle quite similar to the Sonar echo sounding technique used in submarine warfare. However, the range of ultrasonic frequencies employed for material inspection is different and extends from about 0.2 to 100 megacycles.

In the ultrasonic pulse echo method, a single ultrasonic transducer acts as transmitter and receiver of ultrasonic signals. The transducer, which is coupled to the surface of the test specimen, transmits a pulse of ultrasonic energy into the specimen and is then ready to receive any echoes reflected from internal defects or from the back surface of the specimen. The received echoes are amplified and displayed as vertical indications on a cathode ray tube. The X-deflection plates of the cathode ray tube are usually connected to a time base generator to provide a means for measuring the travel time of the initially transmitted ultrasonic pulse from the transducer to a specific defect. From the knowledge of the travel time the distance between the defect and the test surface can be deduced, if the velocity of ultrasonic waves in the tested material has previously been determined. The two remaining coordinates of the defect location can be derived by scanning the test specimen surface with the ultrasonic transducer and noting the position at which the defect echo amplitude is the largest. If the defect is much greater than the width of the ultrasonic beam used for scanning the test specimen, the procedure will even yield the geometric outline of the defect. In this case it is generally easy to assess the severity of a flaw on the basis of the ultrasonic test results. However, if the flaw is of the same order of magnitude or smaller than the beam width, the flaw geometry is not revealed by the pulse echo test and the interpretation of test results is, therefore, quite a problem.

In the past, numerous attempts have been made by researchers to determine the size of defects which are smaller than the ultrasonic beam width. (In the near radiation field, the beam width is equal to the ultrasonic transducer diameter). One such attempt is to compare the defect echo amplitude to indications derived from artificial flaws of known size. Although great efforts have been expended on this approach, in most cases the results are not satisfactory.

A different technique, which has received much less attention because of experimental difficulties, offers more promise as a solution to the problem. In this technique, pulse echo tests are carried out at various ultrasonic frequencies rather than at only one particular frequency. Thus, the specimen is subjected to ultrasound having different wavelengths. Since the reflection of ultrasonic energy from a

defect depends on the ratio of the defect magnitude to the ultrasonic wavelength, the defect echo amplitude is influenced by changes of the ultrasonic wavelength. A determination of the frequency dependence of the defect echo amplitude will, therefore, yield information on the defect geometry.

Unfortunately, the practical application of the aforementioned concept has certain difficulties. Although most commercial pulse echo test instruments are so designed that they can be adjusted for various ultrasonic frequencies, the successive application of different ultrasonic frequencies to a single test specimen would be very cumbersome. Retuning of the transmitter and/or amplifier would be required and, in addition, exchanging of the transducers would be necessary. The latter necessity is a most objectionable feature of the successive procedure because by changing transducers a variation of the transducer-to-specimen coupling conditions may be introduced and, thus, the reliability of the test may be impaired.

To overcome the difficulties encountered with procedures employing a successive application of different ultrasonic frequencies, a novel method was developed at Watertown Arsenal Laboratories which permits the simultaneous use of a wide range of ultrasonic frequencies in pulse echo testing.

THEORETICAL INVESTIGATION

The first step in the development of the novel multifrequency pulse echo test was to investigate how ultrasonic signals could be produced which would contain energy covering a wide range of frequencies. A theoretical study of this problem revealed that single polarity as well as carrier frequency pulses having a rectangular outline would be suitable as sources of multifrequency or, to borrow a term from optics, "white" energy. The spectral energy functions for two representative pulses of such type are given by the equations shown in Figure 1. Figure 2 shows the spectra derived from the formulae of Figure 1 for the two basic pulses (Figures 2a and 2b) and for a carrier frequency pulse that comprises three cycles (Figure 2c). Absolute spectral amplitudes are plotted on a logarithmic scale versus frequency on a linear scale. The reason for selecting this type of plot was that curves thus obtained, to a large extent, resembled displays produced by the electronic spectrum analyzer available for the experimental work.

Comparison of the spectra depicted by Figure 2 indicates that the third pulse, consisting of three cycles of the carrier frequency, contains higher frequencies at about the same level as the two other pulses. Although the spectral amplitude in the vicinity of the carrier frequency is relatively larger, the 3-cycle pulse can still be regarded as a fairly "white" signal. This result is of practical importance because the

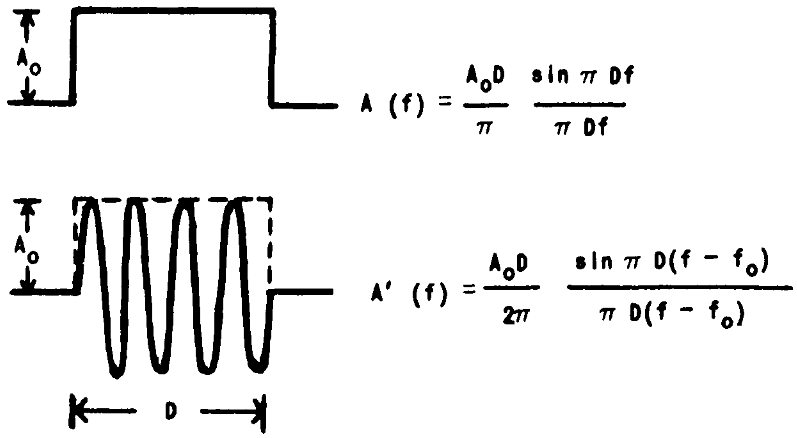

Figure 1. SPECTRAL FUNCTIONS A (f) AND A′ (f) OF SINGLE POLARITY AND CARRIER FREQUENCY PULSES WITH RECTANGULAR ENVELOPES
A_0 = Pulse Amplitude; D = Pulse Length; f = Frequency; f_0 = Carrier Frequency

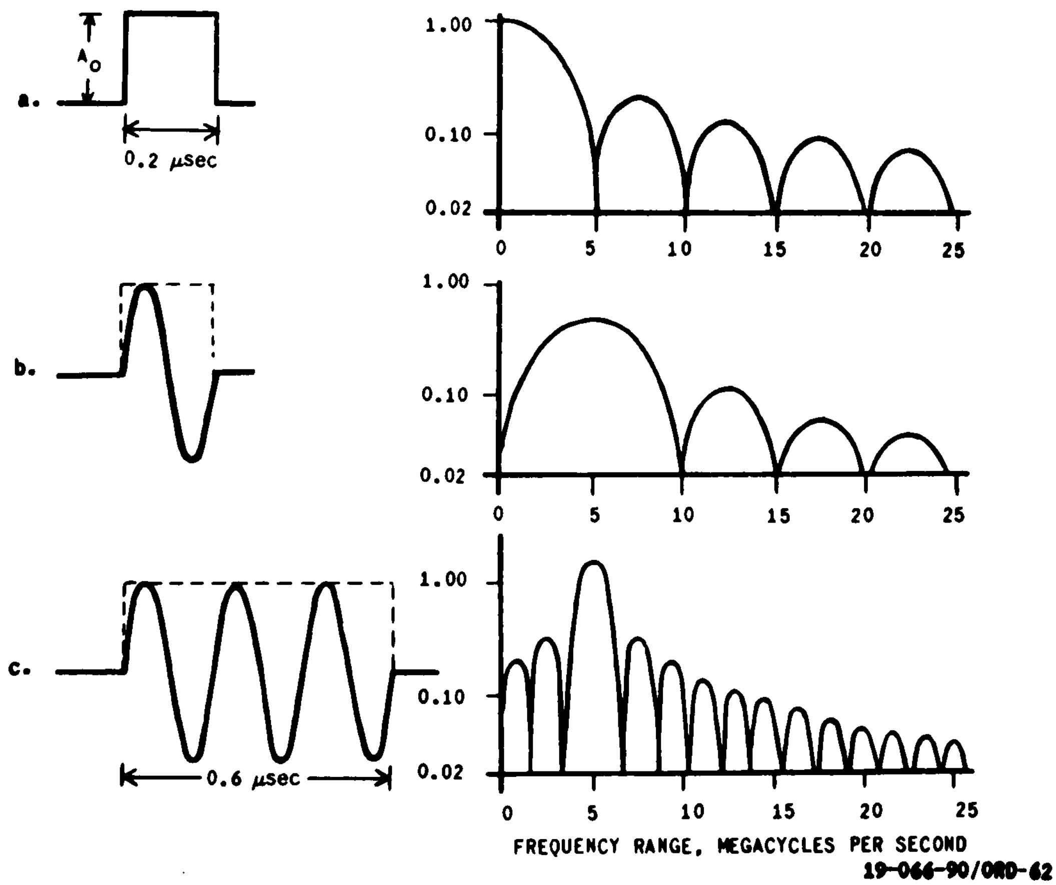

Figure 2. SPECTRA OF SINGLE POLARITY AND CARRIER FREQUENCY PULSES WITH RECTANGULAR ENVELOPE

generation of an ultrasonic signal consisting of three cycles proved to be feasible.

PRELIMINARY EXPERIMENTS

By applying rectangular voltage pulses of single polarity to barium titanate transducers it was possible to produce "white" ultrasonic pulses similar to the last pulse illustrated by Figure 2. Other piezoelectric materials which were also examined did not yield equally favorable results. The upper trace of Figure 3 shows an ultrasonic signal and its

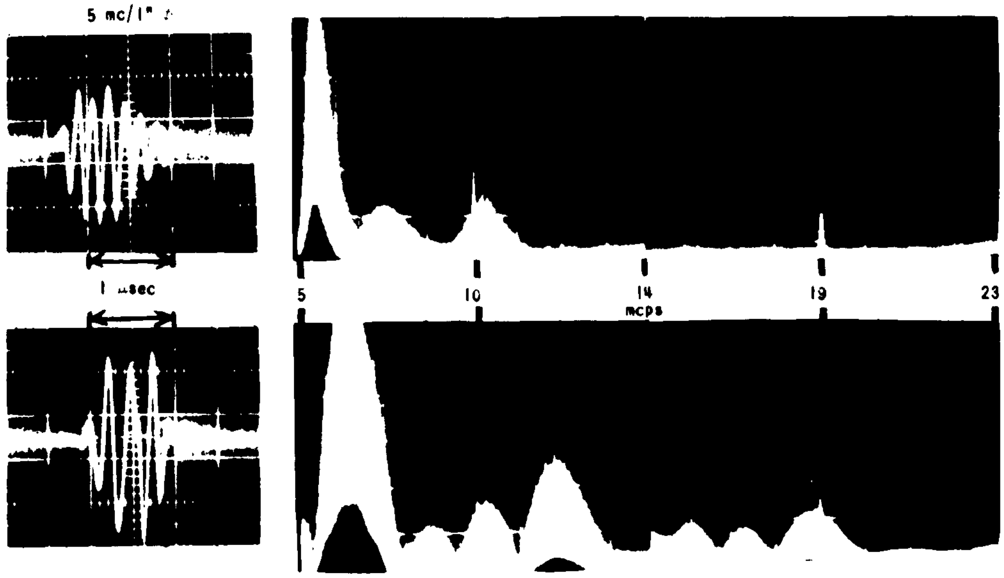

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Figure 3. SPECTRA OF ULTRASONIC PULSES WITH ROUND AND WITH RECTANGULAR ENVELOPE

spectrum obtained with a transducer having less desirable characteristics. The pulse exhibits a build-up and decay of the oscillation slower than demonstrated by the lower trace of Figure 3 which was derived from the specially selected barium titanate transducer. Correspondingly, the spectra of the two pulses show significant differences. While the upper spectrum can be considered as almost monochromatic, the lower spectrum exhibits a relatively large content of higher frequencies. Although the energy distribution in the spectrum differs somewhat from the theoretical case illustrated by Figure 2, the signal obtained from the barium titanate transducer proved to be quite useful as a "white" pulse for the purpose of relative defect geometry analysis.

APPLICATION

"White" ultrasonic pulses of the type illustrated by the lower trace of Figure 3 were employed for experiments on specimens with fabricated

flaws of various geometries. The experiments were carried out with compressional ultrasonic waves and relatively large specimens. The velocity of ultrasonic waves could, therefore, be regarded as a material constant. Hence, the ultrasonic wavelength was inversely proportional to the frequency. Since aluminum specimens were used, the wavelength of a 10-megacycle signal, for instance, was 0.024 inch.

The purpose of the first series of experiments was to demonstrate that "white" ultrasonic pulses were superior to monochromatic test signals with regard to their ability to determine the configuration of hidden defects. The same pair of test specimens was, therefore, subjected to an inspection by the two different test systems schematically outlined by Figure 4. The system depicted by Figure 4a possesses a relatively narrow band width and, hence, uses essentially monochromatic ultrasonic energy. The pulse associated with the narrow band width system is relatively long and has a round contour. A test system which utilizes wide band width components is shown by Figure 4b together with the much shorter ultrasonic pulse it produces.

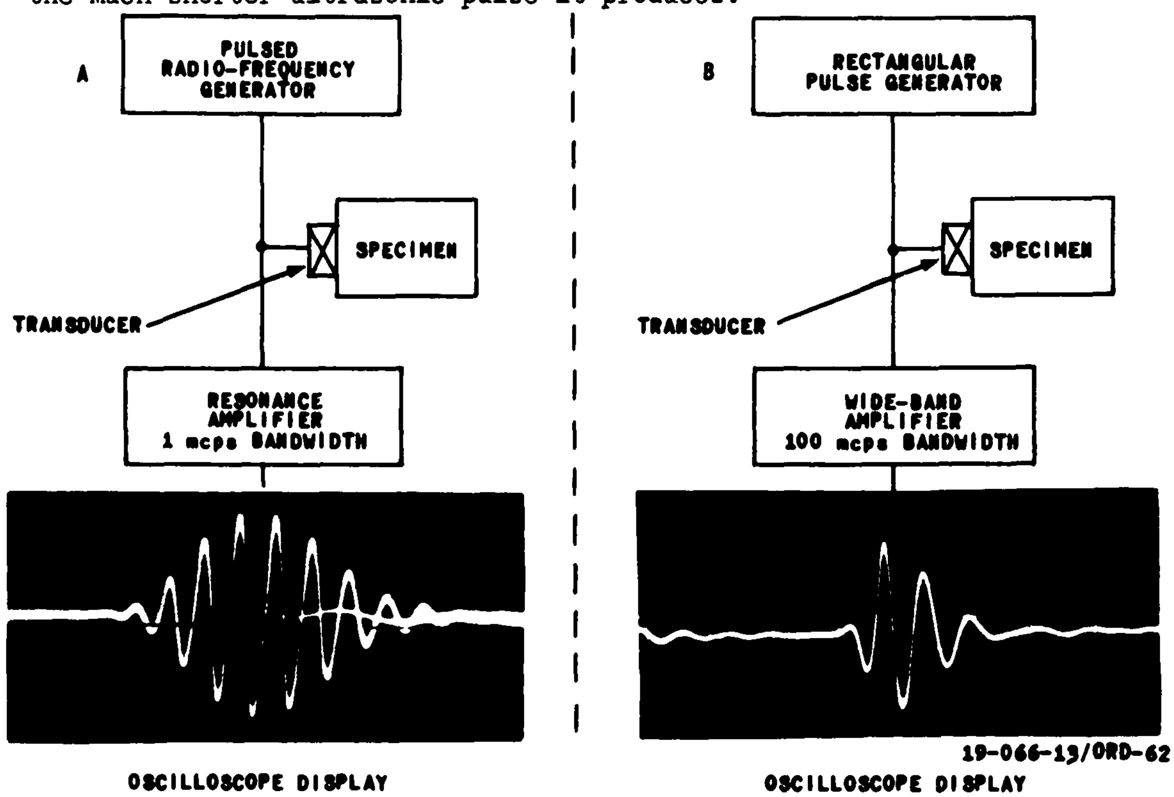
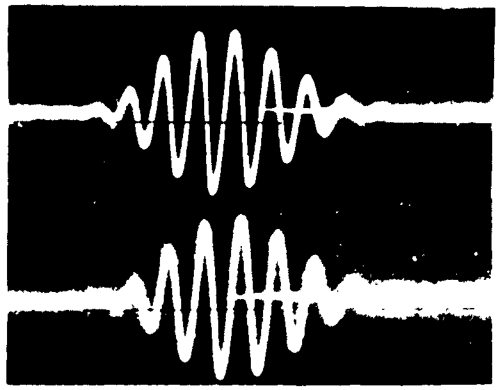


Figure 4. BLOCK DIAGRAMS OF CONVENTIONAL NARROW-BAND (A) AND NOVEL WIDE-BAND (B) ULTRASONIC TEST SYSTEMS AND RESULTANT PULSE SHAPES.

Figures 5 and 6 illustrate the results obtained from the inspection of two aluminum test specimens provided with cylindrical holes of 1/8- and 1/32-inch diameter respectively. (In this and in all the following experiments, the amplifier gain was so adjusted that the peak amplitudes of the defect echoes were always the same, thus facilitating comparisons of pulse shapes and pulse spectra.)



1/8-IN.-DIAM HOLE

1/32-IN.-DIAM HOLE

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Figure 5. ULTRASONIC REFLECTIONS OBTAINED FROM 1/8-INCH AND 1/32-INCH HOLES WITH A NARROW-BAND TEST INSTRUMENT

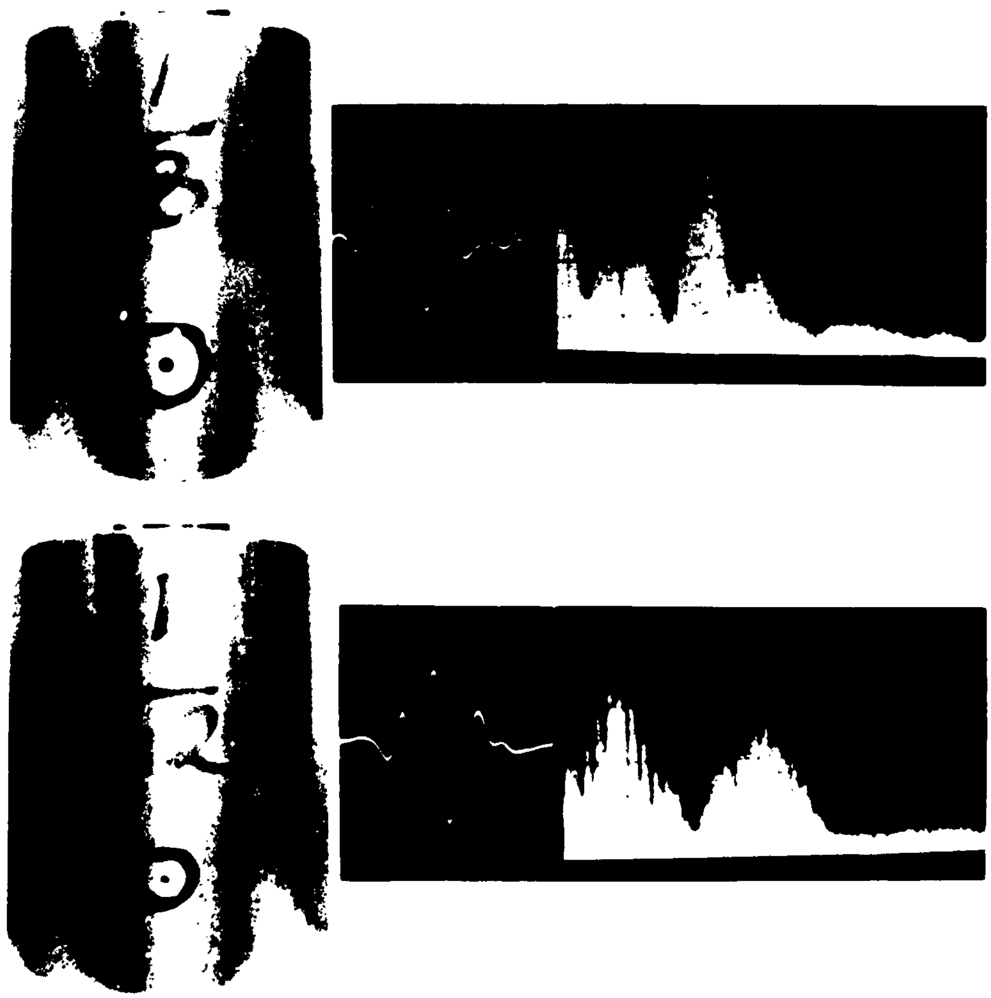

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Figure 6. ULTRASONIC REFLECTIONS OBTAINED FROM 1/8-INCH AND 1/32-INCH HOLES WITH A WIDE-BAND TEST INSTRUMENT

Figure 5, which shows defect echoes obtained with the narrow band width system, indicates that no significant differences in pulse contour could be observed if the 1/8-inch and 1/32-inch holes reflected monochromatic pulses. In contrast to this result, the pulse shapes and spectra of "white" pulse reflections, which are illustrated by Figure 6, show significant differences. The distinguishing characteristic of the pulse shapes are the amplitudes of the second cycles indicated by markers on Figure 6. In addition, the pulse spectra exhibit pronounced differences, a fact which is not surprising because, according to the Fourier theory, the time function can be strictly correlated to the frequency function. (Spectra of Figures 6, 7, and 8 cover a range of 5 to 15 mcps.)

In evaluating the results illustrated by Figure 6, it is important to note that the two cylindrical flaws, which closely represent the practical case of stringer inclusions, had equal length and differed only in diameter. Hence, the fact that it is possible to distinguish between these flaws is quite significant.

Further experiments were carried out by applying the "white" pulse test method to aluminum cylinders provided with axially drilled flat-bottom holes as indicated by Figure 7. These artificial defects were introduced into the specimens to simulate internal porosity. The pulse shapes and spectra derived from such defects are shown by Figure 7. On the basis of these test results, it is possible to distinguish between a porosity consisting of a large number of small holes and a porosity consisting of a small number of large holes, although the total reflecting cross-section in each case is about the same. Information concerning the size of the individual cavities which can thus be obtained is very important for practical quality inspection because small holes can sometimes be eliminated by a subsequent forging process while large holes would be a basis for rejection of the part under inspection.

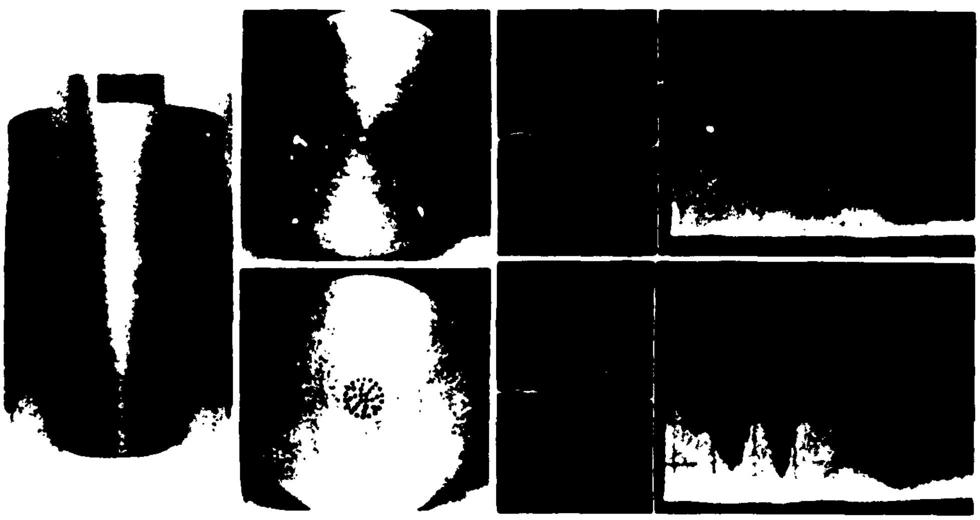

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Figure 7. SPECIMENS WITH ARTIFICIAL POROSITIES, DEFECT ECHOES AND ECHO SPECTRA.

As a final example of applications for the ultrasonic pulse analysis method the inspection for internal cracks is considered. The interpretation of ultrasonic test results obtained from specimens having internal cracks is extremely difficult if conventional monochromatic methods are employed. This difficulty exists because by such methods only the amplitude of the reflection is available as a criterion. The echo amplitude, however, is strongly influenced by the orientation of the crack with reference to the surface of the specimen to which the transducer is coupled. A relatively large crack, for instance, is liable to be misinterpreted as being an insignificant defect if it is so oriented that at the specific test frequency only a small amount of ultrasonic energy is reflected back to the transducer. In the pulse analysis technique, however, errors of this nature are less likely to occur because amplitude differences between individual frequency components of a "white" ultrasonic signal yield additional information.

To investigate the effectiveness of the pulse analysis method for the inspection of internal cracks, the aluminum specimens illustrated in Figure 8 were prepared. The specimens contained cuts at angles of 10,

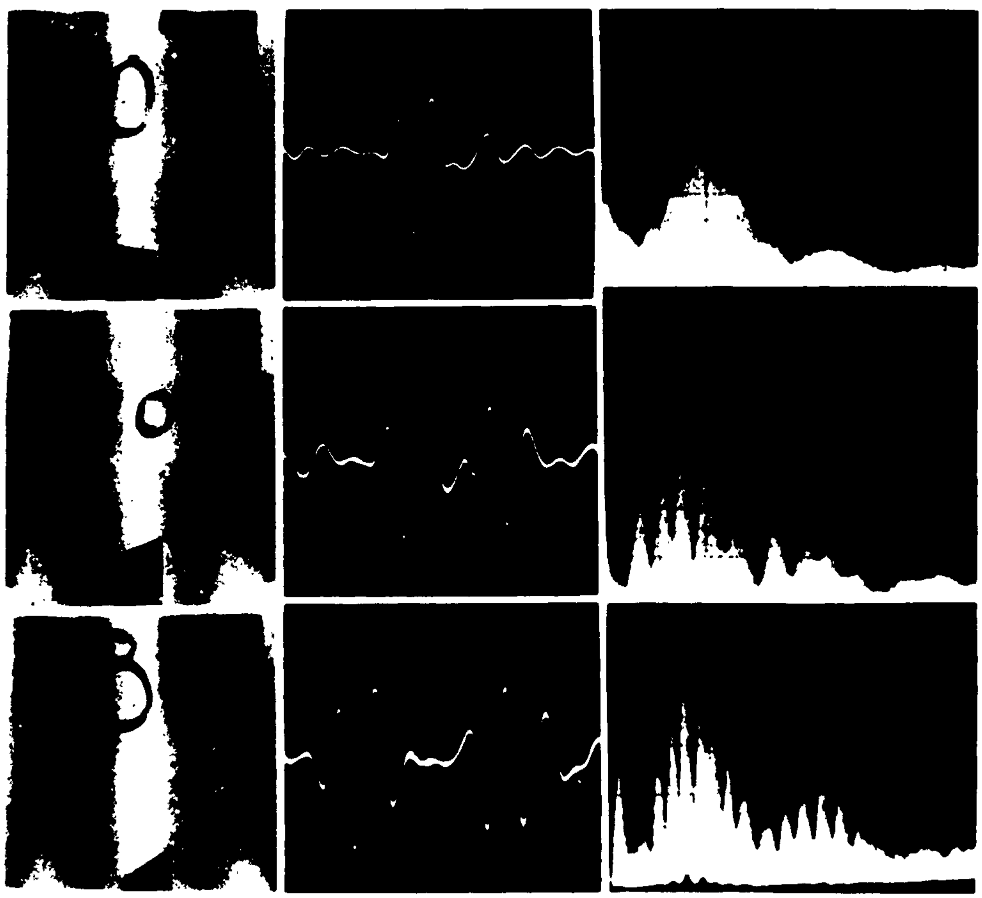

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Figure 8. SPECIMENS WITH ANGLE CUTS, DEFECT ECHOES, AND ECHO SPECTRA.

20 and 30 degrees to the test surface to simulate internal cracks of various orientations. Figure 8 shows also the defect echo and echo spectrum obtained from each specimen and it is noted that pulse shapes and spectra exhibit very significant differences for the various defect orientations.

CONCLUSIONS

The results of the experiments conducted indicate that the effectiveness of ultrasonic pulse echo testing can be greatly enhanced by the introduction of multifrequency signals and defect echo analysis. The main benefit to be derived from this innovation is that differences in the configuration or orientation of concealed defects can be determined.

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